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A CONCEPTUAL MODEL OF WIND EROSION OF SOIL SURFACES BY SALTATING PARTICLES

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ABSTRACT

A conceptual model is described for the prediction of wind erosion rates dependent on the distribution of impact energy delivered to the surface by saltating grains, $P[Ei]$, and the distribution of local surface strength, $P[Es]$. Methods are presented for the measurement of both distributions and consequent loss of material from the bed. It is concluded that saltating sand grains can rupture weak crusts under even moderate wind conditions, and that the rate of erosion will depend on the shape of the distribution tails. Copyright © 1999 John Wiley & Sons, Ltd.

KEY WORDS: wind erosion; saltation; impact energy; surface strength

INTRODUCTION

The terms wind erosion and dust emission are both used to describe the interaction of wind and a sediment surface. Although these two terms are sometimes used interchangeably they do convey distinctive, but complementary, aspects of the same phenomenon. The term wind erosion highlights *loss of material from the sediment*, whereas the term dust emission emphasizes the *gain of material to the atmosphere*. This distinction is made clearer when the practical problems resulting from the phenomenon are considered. Some problems, such as human respiratory illnesses or traffic accidents due to reduced visibility, are associated with the transport of fine material in the atmosphere (Holt, 1987; Buritt and Hyers, 1981). Other problems, such as reduced soil fertility, are associated with a loss of fine particles from the soil or sediment (Zobeck and Fryrear, 1986). In predicting the effects of problems associated with *wind erosion*, both the amount and the size distribution of the lost material are important quantities. In predicting the effect of *dust emission*, the proportion of finer particles in the released material is of particular importance. Short-range transport of less than 100 km consists of material $<50\ \mu$m, while longer-range transport is restricted to particles smaller than 10 μm (Pewe, 1981).

The distinction we have drawn between *wind erosion* and *dust emission* also influences the choice of measurement techniques. A measurement of erosion rate (loss) is not the same as a measurement of dust concentration (even if made very close to the source), because transport processes begin sorting material by size, shape and density immediately after it is released. It is reasonably practical, at least in laboratory conditions, to measure erosion rate either by mass differencing (Zobeck, 1991) or by surface profiling (Rice *et al.*, 1996a). In contrast, it is beyond the scope of current technology to measure accurately the complete size distribution of released material. Any measurement of dust concentration provides a sorted subset of the size distribution of the released material which is, to some extent, dependent on the location and method of the measurement with respect to the source of the dust.

This paper presents a conceptual model of wind erosion by saltating grains in which the erosion rate is determined by the strength of the surface and the energy delivered to the surface by the saltating grains. A key

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element of the model is that it is probabilistic, the saltating grains and the surface strength being represented by probability distributions. The relationship between these three variables is shown conceptually in Figure 1. In this model the erosion rate of the sediment is determined by the distribution of impact energy delivered to the surface by the saltating grains, $P[Ei]$ and the distribution of local surface strength, $P[Es]$. The rate of erosion can be seen to be highly dependent on the degree of overlap between the two distributions, which is determined by the shape of the tails.

The reason for this choice of variables is that together they represent a closed system. If a measurement of the released material were to be used as the dependent variable it would lead to an open system, which is less useful in developing a predictive tool. It is recognized, however, that many practical problems require a knowledge of the size distribution of the released material.

Use of the model to predict erosion rates for a variety of sediment surfaces as a function of surface strength and wind speed requires an understanding of the small-scale physical processes involved in saltation and measurements of the three variables involved. These are discussed below.

SALTATING PARTICLES

During the last 10 years experimental and theoretical studies have significantly changed our perception of how saltating particles are moved by the wind. Until the mid-1980s Bagnold's (1941) idea that saltating particles rebound from a surface at 90° and follow a characteristic path length was generally accepted. However, wind tunnel experiments using high-speed cine-photography demonstrated that saltating grains impacted the surface at an angle with the horizontal of about 10° and on average rebounded at 25°, although the latter depended on particle size and on the configuration and slope of the bed (Willetts and Rice, 1985, 1986, 1989; McEwan *et al.*, 1992; Rice *et al.*, 1995, 1996b). With non-cohesive sand-sized particulate surfaces the saltating particles splashed up previously stationary grains. These data, together with collision data generated from computer simulations, permitted satisfactory models of saltation to be constructed, which included the effects of the sediment on the wind and vice versa (Anderson and Haff, 1988; McEwan and Willetts, 1991, 1993; Sorensen, 1991). Because of the stochastic nature of the grain/bed collision, Bagnold's concept of a characteristic trajectory has been replaced by a distribution of particles representing a wide range of saltation trajectories. It is likely that the shape of this distribution (shown as $P[Ei]$ in Figure 1) has a significant effect on erosion rates.

The above saltation models only included particles in the sand-size range, which are non-cohesive and too large to be suspended by turbulent flow. However, when finer particles are present in an erodible surface, as in a soil, there are many more factors (such as cohesion, cementation, crusting, aggregation, packing, etc.) to take into consideration when modelling the process(es) of their release from the surface and entrainment into the flow. Little is known about surface characteristics in terms of probability of erosion, or about the role of saltating particles in releasing surface particles for entrainment into the air (Anderson *et al.*, 1991).

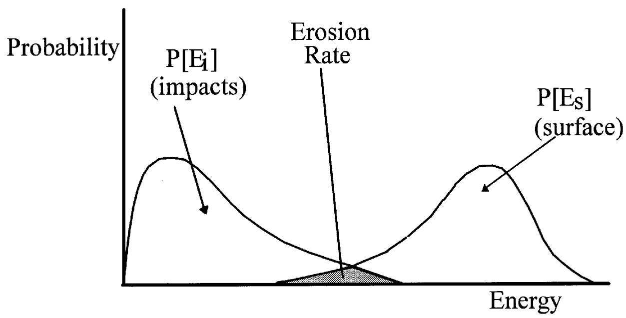

Figure 1. Conceptual model of physical processes

Although the processes involved in surface erosion due to particle impact are poorly understood, it is generally appreciated that saltating grains can be an important factor in dust release. Their interaction with a sediment surface can generate large clouds of dust even when windspeeds are below the threshold for aerodynamic entrainment of fine material (Bagnold, 1960; McTainsh, 1985; Shao *et al.*, 1993). It is well established that threshold velocities for grain transport decrease with decreasing diameter for sandsized particles, but increase again for particles less than about 80 μm (Bagnold, 1941). This upturn is attributable to interparticle cohesion (Iversen *et al.*, 1976). These fine dust particles are therefore not easily entrained by wind alone. Entrainment of particles into the airflow presupposes that they are available at the surface. Saltating grains can provide the energy necessary to rupture some interparticle bonds, thus releasing material for possible entrainment.

IMPACT ENERGY

The wind tunnel studies of Zobeck (1991) and Hagen (1991) have shown that abrasion losses are proportional to the total kinetic energy delivered by impacting saltating particles. Zobeck examined 14 soils, using unconsolidated samples and two levels of consolidation (i.e. crust formation due to simulated rainfall), and Hagen experimented with crusted surfaces and surfaces with a proportion of non-abradable aggregates. In other wind tunnel studies, Shao *et al.*, (1993) demonstrated that dust flux was approximately proportional to the streamwise flux of sand grains allowed to saltate on to a dust bed from an upwind source. Rice *et al.* (1996a) found that the volume of material removed by single saltating grains in unaggregated soil is linearly dependent on the kinetic energy of the impactors, and that dislodgement of surface particles decreases with increasing soil strength.

Where momentum or energy delivered to the surface was measured in the above experiments, this was obtained either from a known abrader flux or from high-speed film. The latter enables observations to be made of individual saltating particles bombarding a sediment surface. However, analysis of films is time-consuming, so the authors have used another imaging technique for following saltating grains as they approach and collide with a sediment surface.

METHODS

Particle imaging

We have used particle tracking velocimetry (PTV) to record sand grains fed into a wind tunnel at a constant rate upwind of a sediment bed (200 $\times$ 50 $\times$ 20 mm). Images were collected on super video tape via a Cohu CCD camera with resolution of 560 $\times$ 450 lines. This was positioned at 90° to and on a level with the bed surface (see Figure 2). An experimental area of the bed was illuminated by a pulsed sheet of laser light produced by the repeated scanning of a narrow laser beam at a high frequency. The light source was an Ar-ion continuous wave laser, which was set at 4 W during these experiments. The scanning box (Optical Flow Systems, Edinburgh) produced a beam width of approximately 3 mm, with a length of up to 15 cm. The scan rate could be set between 80 Hz and 2 kHz (0·5 to 12·5 ms). In order to record several images of saltating particles on one frame, the scan rate normally used was in the fast range, between 0·7 and 2·0 ms. Image analysis software calculates the displacement of the particle between the two images which, with a knowledge of the time interval, gives its velocity.

A typical frame is illustrated in Figure 3, where multiple images of a 250 μm diameter sand grain are recorded as it collides with a bed composed of 2 – 10 mm aggregates. The size of the saltator was known because the introduced particles were pre-sieved into $\frac{1}{4}\phi$ fractions. However, this imaging method can also use software (such as that developed by Lim, 1996) to determine the size of sand particles of unknown diameter. Velocities of the incoming and rebounding particle paths can be readily calculated.

The technique may also be used to obtain additional information on ejected material. Although this is not required for the conceptual model described here, the method has potential for observing and partially quantifying velocities and sizes of material mobilized by the impacting particles. For example, Figure 4a–d

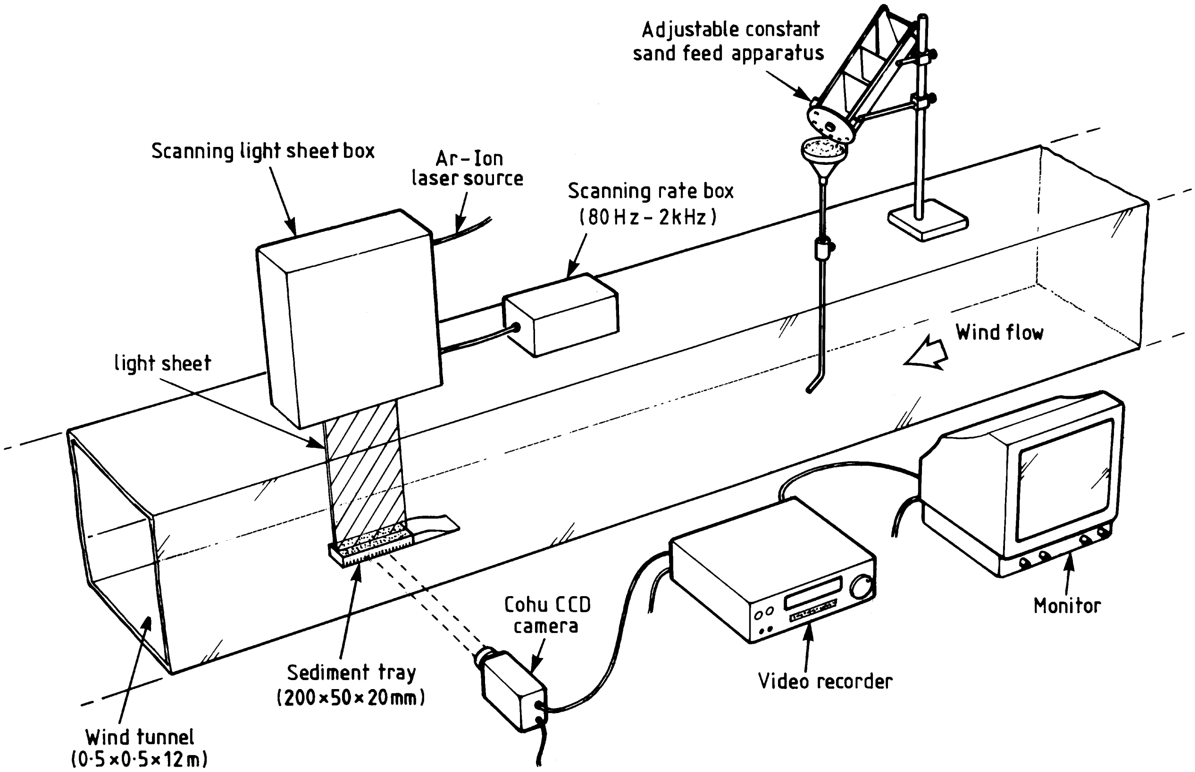

Figure 2. Experimental set-up for recording saltating sand particles impacting a sediment bed

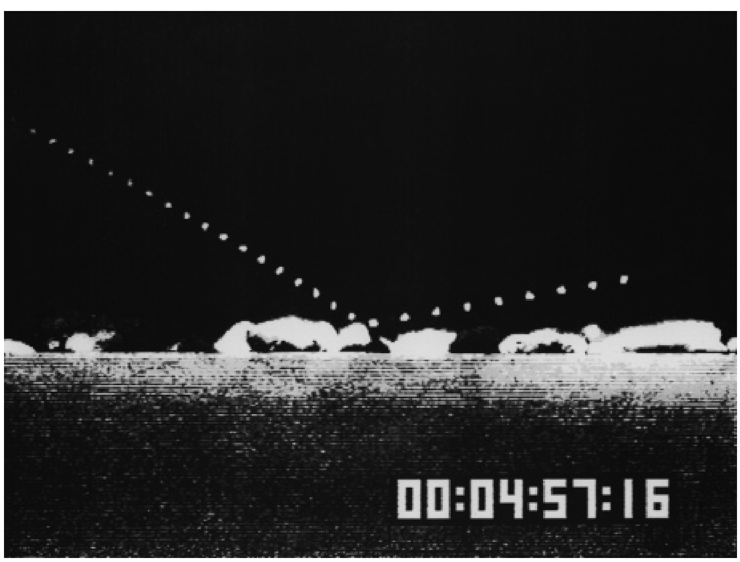

Figure 3. A typical collision of a 250 μm diameter sand grain colliding with a bed composed of 2 – 10 mm aggregates

shows multiple images of 300 μm diameter sand grains colliding with a bed of loose soil <53 μm in diameter. Figure 4a and b have a field-of-view of 50 mm. The ejected grains usually emerge after the saltating particles have left the bed (see Rice *et al.*, 1996a). A smaller field-of-view of 15 mm can be seen on Figure 4c and d. The large cloud of grains mobilized by the saltating particle means that most of the ejecta are initially masked

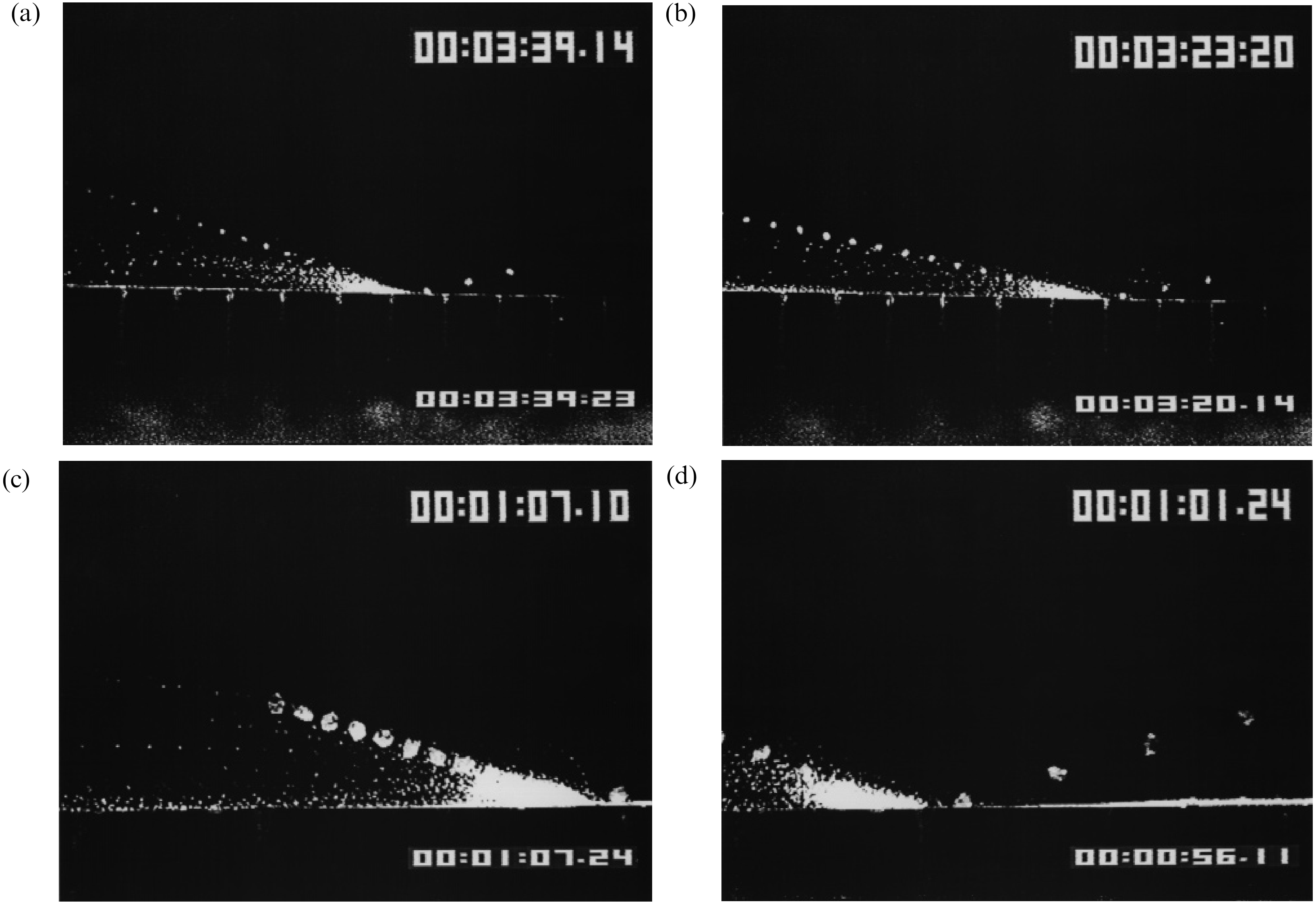

Figure 4. Multiple images of 300 μm saltating sand grains recorded by repeated scanning of a narrow laser beam across a sediment bed of loose soil < 53 μm in diameter. (a) and (b) have a field of view of 50 mm (tick marks represent 5 mm). (c) and (d) have a field of view of 15 mm (again, tick marks represent 5 mm). Windflow is from right to left

by their neighbours. Some of the faster-moving particles, however, can be traced individually. Velocity data for the leading edge of the dispersing cloud of ejected grains can thus be obtained. Unfortunately, this technique is currently not able to resolve particle size where its diameter is less than about 25 μm. Improvement in the resolution is a long-term aim in the development of this technique, since particles much smaller than this are significant in longer-range dust transport. However, as very little is known about the vertical flux of newly ejected dust, even partial data on large dust particles may help clarify the mechanism of ejection.

Surface strength

In order to develop an erosion function, the susceptibility to erosion of a wide range of soils and sediments needs to be measured. The composition of the surface is important, although a large proportion of fine particles does not necessarily imply that they will be easily released. Sediments are not easily eroded if they contain more than 10 per cent clay. Sands and sandy loams are less cohesive and are more susceptible to erosion (Pye, 1989), particularly when any surface crusting has been disturbed. This may also be because they contain sand-sized material, which may be a potential source of abraders. Erosion becomes increasingly difficult when a surface is crusted. Even a weak crust has been shown to reduce the rate of erosion significantly (Gillette *et al.*, 1982), protecting the underlying less cohesive particles from aerodynamic and impact forces. In this situation the role of saltating grains in breaking down the bonding between adjacent particles in surface crusts is clearly an important factor in determining rates of erosion (Rice *et al.*, 1996a). Sand-sized particles frequently remain on the surface after crusting has taken place (Potter, 1990). These grains or others from neighbouring upwind areas readily saltate over the cohesive bed under moderate wind conditions. On impact they deliver kinetic energy to the crust and their collective abrasive capacity is likely to be considerable (Greeley *et al.*, 1984; Hagen, 1984; Anderson, 1986). Abrasion of aggregated and crusted soils by saltating grains has been inferred from studies of aerosols from the Sahara Desert (Gomes *et al.*, 1990). It has also been observed and documented in wind tunnel studies (Hagen, 1991; Zobeck, 1991) and at Owens Lake in the Mojave Desert, (Gillette *et al.*, 1996) and at paddock and regional scale in Australia (Shao *et al.*, 1996).

Standard methods for characterization of soil surfaces in terms of soil strength are not readily adaptable to the characterization of those surface attributes likely to control erodibility. For example, the modulus of rupture test (Richards, 1953) is conventionally performed on remoulded samples and is difficult to modify for undisturbed weak pieces of crust. Similarly, the aggregate stability test of Skidmore and Powers (1982) is not readily adapted to characterize weak crusts. It also attempts to characterize surface properties by a single mean value.

For this reason another method, using a flat-tipped needle penetrometer ($D = 0{\cdot}6$ mm) has been developed by Rice *et al*. (1997). This measures the penetration force as a function of depth at a number of random positions over the surface. The technique provides a distribution of values of surface strength measured at a scale comparable to that of the impacting particles. The strength test can also provide corresponding sets of values for the energy required for penetration. By comparing the distribution of energy required for penetration against the distribution of values for the kinetic energy of bombarding saltating particles it is thus possible to determine potentially erodible surfaces. At its simplest, this technique can be used to indicate what, if any, is the chance of an impacting particle detaching surface material.

The needle penetrometer used here was driven into a surface at a constant rate (0·62) mm min^{-1}) by a small motor geared down to 1 r.p.m. This was supported on a frame and attached by a belt to a wheel that turned a screw at a very slow constant rate. The penetrometer was attached to the bottom of a vertical screw plunger. The method gives a measure of surface strength and a modulus of deformation. It is able to demonstrate significant differences in surface strength, which are not apparent from visual appearance, between artificially prepared crusts produced by spray wetting and by tension wetting. In order to interpret the penetration results and understand the likely mode of interaction between saltating grains and the surface, it was necessary to observe whether the penetrometer tip displaced larger particles or aggregates during penetration, or punctured the surface. This was straightforward to do and meant that results for each surface could be partitioned into values that indicated displacement of surface particles or aggregates, direct

penetration (and hence rupture) of the surface, and values of penetration energy that were large enough to indicate that saltating grains could not rupture the surface or displace aggregates from it and could only abrade it by chipping away small fragments. The needle penetrometer provides a test for characterizing the relative importance of different mechanisms of surface abrasion by saltating particles and provides data towards obtaining a physically based relation between the flux of saltating particles and the rate and type of erosion. It can also be modified for use in the field.

Erosion rate

The erosion rate in this context is measurement of loss of material from the bed. This can be determined by a mass difference technique in which sediment trays are weighed before and after a period of saltation bombardment (Zobeck, 1991). This provides a mean erosion rate for a particular sediment sample. Alternatively, a profiling method may be used. Rice *et al*. (1996a) measured craters made by saltation impacts in a loose fine sediment using a laser profiling technique. The profiler has a measurement spot of 50 μm and so is capable of providing a high-resolution measurement of a sediment surface. A particular advantage of this technique is that it can provide detailed data on the spatial pattern of erosion, as well as mean values for a particular sediment sample. It is therefore a suitable method for measuring erosion during development of the model.

MODELLING WIND EROSION

Figure 5a and b shows the first attempt to develop the conceptual model by using actual data. In Figure 5a two probability distributions are shown. One is the spatial distribution of soil strength of a strongly crusted soil (Glencarse hard-setting soil, 0·5–2 mm aggregates, which had been spray wetted, then dried for 24 h at 40°C), derived from 25 penetrometer measurements. The second distribution is that of the impact energy of more than one hundred 250 μm diameter saltating grains. The impact energy intensity of a grain was calculated as follows:

$$E_i = \frac{\frac{1}{2}\,mass.velocity^2}{area} = \frac{1}{3}\sigma_s\, d\, v^2$$

in which σ_s is sediment density, d is the grain diameter and v is the grain velocity. The particles were assumed to be spherical and to have a diameter of 250 μm. The results shown in Figure 5a indicate that the energy of the impinging grains will not be high enough to rupture any of the interparticle bonds at the surface of the crust. This was confirmed by the fact that the weight of the tray and soil remained constant before and after the period of saltation. Surface profile plots also showed that the crust had not been abraded. In contrast to this, Figure 5b shows probability distributions for a very weak crust, formed on a sandy loam topsoil. Again the aggregate size was 0·5 – 2 mm, and the tray was spray wetted. The overlapping distributions indicate that the saltating particles should possess enough kinetic energy to abrade a large proportion of the surface and rupture interparticle bonds. The wind tunnel test showed that this was indeed so. Erosion was rapid, and once some of the crust was breached, the rest broke up quickly. However, the rate of erosion was difficult to calculate in this case. This was because, once the very thin crust was removed, saltating particles frequently lost all their energy to the bed as they were left embedded in the soft, less cohesive material beneath the crust. Consequently, measurements of weight loss or surface profiles failed to give a true picture of the removal of surface material. Future measurements will therefore need to be done while the crust is still strong enough to permit continuous saltation.

DISCUSSION

Further quantitative development of this model will be the subject of future work. However, the model can be used to make some qualitative deductions concerning the physical processes which influence erosion. The distribution of impact energy delivered by the saltating grains is a function of wind speed. It is conventionally

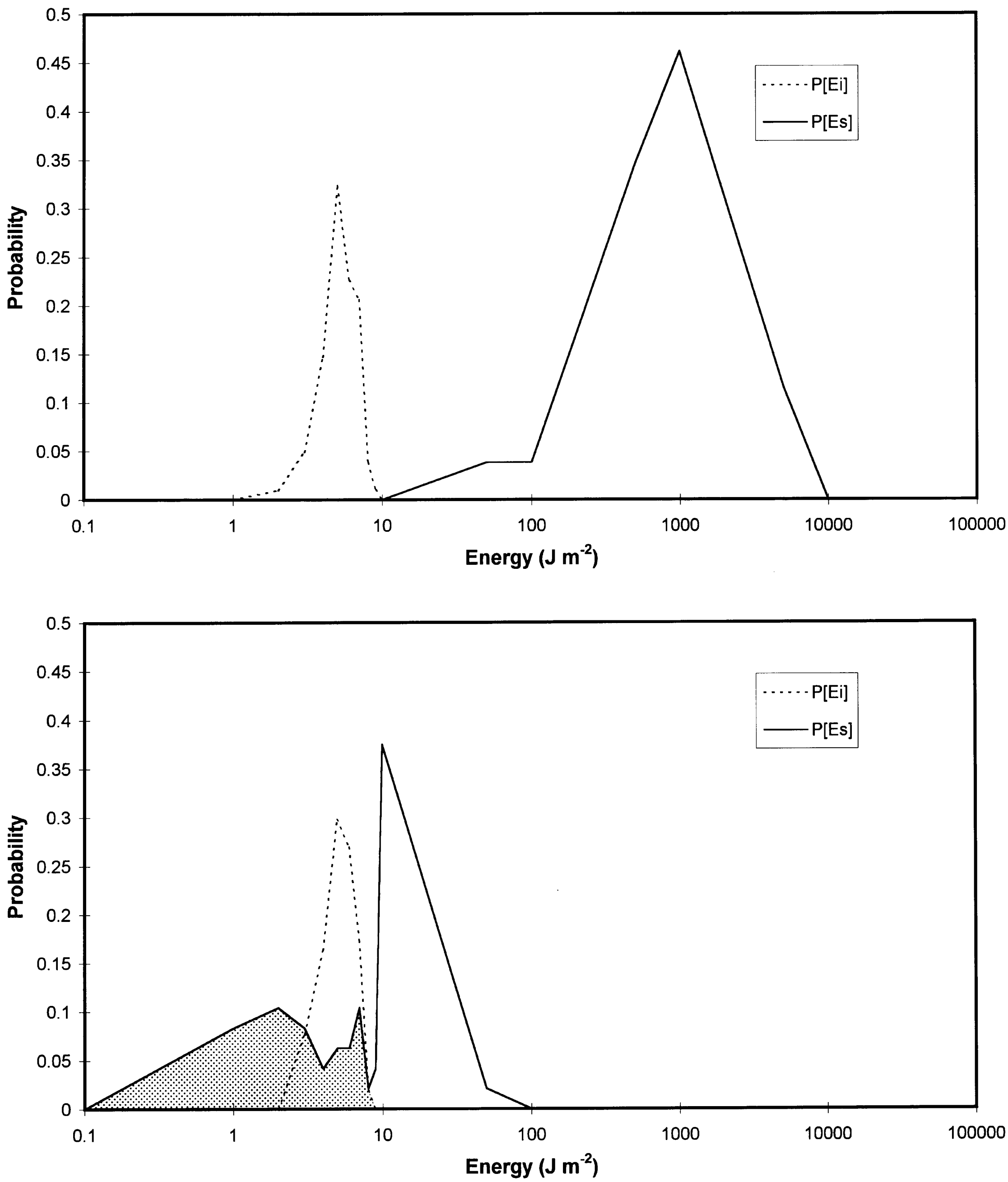

Figure 5. Plots of the probability distributions for the energy of impacting sand particles and the soil penetration energy for (a) a hard-setting soil and (b) a weakly crusted sandy loam topsoil. Note that the shaded area in (b) represents potential erosion of the soil surface

assumed (e.g. Bagnold, 1941; Owen, 1964) that the velocities of the saltating grains scale with the shear velocity, u_*. However, this reasoning obscures the fact that a distribution of particle velocity exists within the saltating grain cloud. The model presented here suggests that, since overlap of the distributions promotes erosion, it is the extreme values of the adjacent tails that are most influential in determining erosion. This provides a case for future modelling and experimental work to take particular account of the high-energy tail

of the distribution of grain trajectories and the low-energy tail of the soil strength distribution. In more quantitative terms it suggests that the higher moments of the distribution (skewness and kurtosis) will be as important as the lower moments (mean and standard deviation) in assessing the erosive potential of a saltating grain cloud.

The distribution of impact energy is not only a function of wind, but is also dependent on the nature of the surface itself. The impact data used in this paper were taken from saltating grains which had previously collided with a fixed sand surface on a wind tunnel floor. Clearly, if the same grains had been required to saltate over a given length of a loose soil surface, they would progressively have lost energy at collision and the subsequent impact energy distribution of the equilibrium saltation cloud would have been diminished. In the limiting case, a surface may be sufficiently compliant so as to make saltation over it unsustainable (as seen in the sandy loam experiment). In this situation erosion would take place at a significantly slower rate as it would require an advancing front of deposited saltating grains to develop, providing a bridgehead into the eroding sediment deposit.

The key point is that there is a feedback between the surface and the distribution of impact energy through the grain. The collision process or 'splash function' is itself dependent on the condition of the sediment surface. In addition, the surface will evolve (Nickling and Gillies, 1989) as deflation takes place. However, it is the specific distributions of energy flux delivered to different strengths of sediment surface that are thought to be influential in the subsequent rate of erosion.

CONCLUSIONS

1. The energy delivered to an existing surface by saltating particles can be described by a distribution reflecting the variation of trajectories and hence, impact energy present in a saltation cloud. The high-energy tail of this distribution is likely to be influential in determining the erosive potential of the saltating population.
2. Soil surfaces are spatially heterogenous in structure and strength. By inference, incipient failure of a crusted surface is likely to occur at its weakest point. Thus it is necessary and important to take account of the spatial distribution of surface strength, in particular the weaker tail of the distribution.

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